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Report Title

Scalable Spin Qubit Circuits with Quantum Dots

ABSTRACT

Double and triple coupled quantum dots have been fabricated by planar and vertical technology to contain just a few electrons in each dot. Electron imaging by scanning probe microscopy with the capability of wavefunction mapping in quantum dots has been demonstrated. Gate voltage and magnetic field control of charge and spin states, as well as exchange coupling between electron spins and between electron and nuclear spins have been achieved. Coherent nuclear spin operations and square-root-of-swap operation between two electrons on a time scale inferior at 1ns have been realized. Meanwhile exchange coupling in various dot configurations has been calculated by realistic simulations in good agreement with experiment. Spin relaxation and decoherence mechanisms in quantum dots have been identified and their time constants measured (by spin echo) in good agreement with theory. Single-shot read-out of electron spin by charge state correlation has been demonstrated to be very fast and robust to electrostatic noise even at finite temperature exceeding state splitting.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

(since July 31, 2006-last progress report)

1. D.V. Melnikov, L-X Zhang and J.P. Leburton “"Exchange Coupling Between Two Electrons in Double Quantum Dot Structures" invited review article in “Current Opinion in Solid State & Materials Science”, ELSEVIER, vol.10 (2007) (invited)
2. D. V. Melnikov and J.P. Leburton, “ Transport Spectroscopy in Vertical Quantum Dots” in "Highlights on Spectroscopies of Semiconductors and Nanostructures", in honor of Angiolino Stella, Eds. G. Guizzetti, L. C. Andreani , F. Marabelli and M. Patrini, the Italian Physical Society (SIF) (2007) (in press). (Invited)
3. D.V. Melnikov, A. Taha and N. Sobh and J.P. Leburton “Coulomb localization and exchange modulation in two-electron coupled quantum dots” Phys. Rev. B. 74 041309 (R) (2006)
4. D. G. Austing, G. Yu, C. Payette, J. A. Gupta, M. Korkusinski, and G. C. Aers “Probing by transport the single-particle energy spectrum up to high energy of one quantum dot with the ground state of an ad-jacent weakly coupled quantum dot”, , Physica Status Solidi (a), 2007 (in press).
5. Jorden A. Van Dam, Yuli V. Nazarov, Erik P.A.M. Bakkers, Silvano De Franceschi and Leo P. Kouwenhoven, . “Supercurrent reversal in quantum dots”, Nature 442, 667-670 (2006)
6. F.H.L. Koppens, C. Buizert, K.J. Tielrooij, I.T. Vink, K.C. Nowack, T. Meunier, L.P. Kouwenhoven and L.M.K. Vandersypen, “. Driven coherent oscillations of a single electron spin in a quantum dot, Nature 442, 766-771 (2006)
7. Pascal Simon, Daniel Loss, “Nuclear spin ferromagnetic phase transition in an interacting 2D electron gas”, cond-mat/0611292.
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10. W. A. Coish, E. A. Yuzbashyan (Rutgers University), B. L. Altshuler (Columbia University), Daniel Loss, “Quantum vs. classical hyperfine-induced dynamics in a quantum dot” , to appear in JAP; cond-mat/0610633.
11. W. A. Coish, Daniel Loss, “Exchange-controlled single-spin rotations in quantum dots” cond-mat/0610443.
12. Jörg Lehmann, Daniel Loss, “ Sequential Tunneling through Anisotropic Heisenberg Spin Rings” cond-mat/0608642.
13. Karyn Le Hur (Yale), Pascal Simon, and Daniel Loss, “Transport through a quantum dot with SU(4) Kondo entanglement” Phys. Rev. B 75, 035332 (2007).
14. W. A. Coish, Vitaly N. Golovach, J. Carlos Egues, Daniel Loss, “Measurement, control, and decay of quantum-dot spins” , Physica Status Solidi (b) 243, 3658 (2006).
15. Esmerindo S. Bernardes, John Schliemann, J. Carlos Egues, Daniel Loss, “Spin-orbit interaction in symmetric wells and cycloidal orbits without magnetic fields”, cond-mat/0607218.
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17. Denis V. Bulaev, Daniel Loss, “Electric Dipole Spin Resonance for Heavy Holes in Quantum Dots” cond-mat/0608410.
18. W. A. Coish, Daniel Loss, “Quantum computing with spins in solids” cond-mat/0606550 (Contribution to the Handbook of Magnetism and Advanced Magnetic Materials, vol. 5, Wiley)
19. D.Klauser, W. A. Coish, Daniel Loss, “Quantum-dot spin qubit and hyperfine interaction” to appear in Advances in Solid State Physics vol. 46, 2006.
20. M.R. Graeber, W.A. Coish, C. Hoffmann, M. Weiss, J. Furer, S. Oberholzer, D. Loss, C. Schoenenberger, “Molecular states in carbon nanotube double quantum dots” Phys. Rev. B 74, 075427 (2006).
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22. Vitaly N. Golovach, Massoud Borhani, Daniel Loss, “Electric Dipole Induced Spin Resonance in Quantum Dots” Phys. Rev. B 74, 165319 (2006).
23. Oliver Gywat (UCSB), Florian Meier (UCSB), Daniel Loss, D. D. Awschalom (UCSB), “Dynamics of Coupled Qubits Interacting with an Off-Resonant Cavity”, Phys. Rev. B 73, 125336 (2006).
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manipulating, and measuring quantum states on a chip”, Physica E 35, 251-256 (2006).
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41. P. Fallahi, K.E. Aidala, R.M. Westervelt, M. Hanson and A.C. Gossard, "Imaging a Few-Electron Quantum Dot in a Magnetic Field", Appl. Phys. Lett., submitted (2006).

Number of Papers published in peer-reviewed journals: 41.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

(since July 31, 2006-last progress report)

1. L-X Zhang, D. V. Melnikov and J.P. Leburton, “Engineering Exchange Interaction in Coupled Elongated Quantum Dots” Abstrract book of the IEEE-NANO-2006 Conference, Cincinnati, OH, July 16-21, 2006.
2. J.P. Leburton “Coulomb interaction and entanglement in coupled quantum dots: simulation and reality” the Third FEYNMAN FESTIVAL, University of Maryland, College Park, MD, 25-29 August 2006 (Invited)
3. J.P. Leburton "Multiscale simulation of electron entanglement in coupled quantum dots", International Topical Workshop "Tera- and Nano-Devices: Physics and Modeling", Aizu-Wakamatsu, Japan in October 16-19, 2006. (Invited)
4. L.P. Kouwenhoven “Spin qubits with quantum dots” Physics Colloquium, Oxford University, Oxford, 27 October 2006.
5. L.P. Kouwenhoven “Single electron spins in quantum dots” Physics Colloquium, Radboud University Nijmegen, 14 November 2006.
6. L.P. Kouwenhoven, “Single electron spins in quantum dots”, Physics Colloquium, FOM-AMOLF Institute, Amsterdam, 27 November 2006.
7. L.P. Kouwenhoven, “Quantum dot Josephson junctions” 374th WE-Heraeus-Seminar on “Spin physics of superconducting heterostructures”, 10-13 December 2006, Bad Honnef, Germany (invited talk on 12 December).
8. L.M.K.Vandersypen, . International conference on Nanoscience and Technology (ICN+T 2006), Basel, Switzerland, Aug. 2006.
9. L.M.K.Vandersypen, Nanophysics: from fundamentals to applications, 6th Rencontres du Vietnam, Hanoi, Vietnam, Aug 2006
10. L.M.K.Vandersypen, School lecture, MCRTN School/Workshop, Keszthely, Hungary, Aug 2006
11. L.M.K.Vandersypen, Physics Colloquium, Leiden University, The Netherlands, 29 Sep 2006
12. L.M.K.Vandersypen, Nanoelectronics Days, Aachen, Germany, Oct 2006.
13. L.M.K.Vandersypen, van der Waals colloquium, University of Amsterdam, The Netherlands, 28 Nov 2006.
14. L.M.K.Vandersypen, Quantum dot spintronics workshop, Bochum, Germany, Dec 2006.
15. Y. Igarashi*, M. Jung, M. Yamamoto, A. Oiwa, T. Machida, K. Hirakawa, S. Taruch "Kondo Resonance in a Single InAs Quantum Dot Probed By Nanogap Electrodes" ICN+T2006, International Conference Nanoscience and Technology July30-Augsut4, 2006, Basel, Switzerland.
16. K. Hitachi, J. Sugawa, M. Yamamoto,S. Tarucha “Spin filtering and spin relaxation in a GaAs quantum dot”, 4th International Conference on Physics and Application of Spin-related Phenomena in Semiconductors,(PASPS2006), Augst 15-18,2006, Sendai Japan.
17. Seigo Tarucha, “Application of slanting Zeeman field for implementing spin qubits and spin raedout with quantum dots”, 2006 US-Japan Workshop on Quantum Information Science in Hawaii, Oct 16-20,2006, Hawaii,U.S.A.,
18. Seigo Tarucha, “New scheme of spin qubits driven by ac electric field” The IEEE Nanotechnology Materials and Devices Conference (IEEE NMDC) ,Oct22-25,2006, Gyeongju, Korea.
19. Seigo Tarucha, “Dynamical nuclear spin polarization induced by hyperfine mediated singlet-triplet transition in coupled quantum dots” 2007Aspen Winter Conference on Condensed Matter Physics,Jan 14-20.2007Aspen,U.S.A.
20. Seigo Tarucha, “The Kondo effect for a semiconductor quantum dot with superconducting contact leads”, UBC-Tokyo Conference on Novel Quantum Matter PITP/AMPEL/University of Tokyo conference UBC, January 28-31, 2007 Vancouver,Canada

Number of Presentations: 20.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

(since July 31, 2006-last progress report)

1. D.V. Melnikov and J.P. Leburton, “ Single Particle State Mixing and Coulomb Localization in Two- Electron Realistic Coupled Quantum Dots”, Phys. Stat. Solidi, Proc. ICSNN-06, Istanbul, TK July 30-Aug.4, 2006 (in press)
2. L-X Zhang, D. V. Melnikov and J.P. Leburton, “Engineering Exchange coupling in Coupled Elliptic Quantum Dots”, cond-mat/0610281; Special issue of the IEEE Transactions on Nanotechnology of the IEEE-NANO-2006 Conference, Cincinnati, OH, July 16-21, 2006.
3. D. G. Austing, G. Yu, C. Payette, J. A. Gupta, C. Dharma-Wardana, and G. C. Aers, “High Bias Magneto-transport Through Two Weakly Coupled Vertical Quantum Dots and Quantum Wells” Proceedings of the 2006 International Conference on the Physics of Semiconductors, to be published 2007.

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 3

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED	
Lingxiao Zhang (UIUC)	0.50	No
Ronald Hanson (Delft)	1.00	No
L.H. Willem van Beveren (Delft)	1.00	No
B. Coish (2006, Basel)	1.00	No
H.A. Engel (2004, Basel)	1.00	No
Alex johnson (Harvard)	0.50	No
Ron Potok (Harvard)	0.50	No
Joshua Folk (Harvard)	0.50	No
Leo Di Carlo (Harvard)	0.50	No
Jacob Taylor (Harvard)	0.50	No
Edward Laird (Harvard)	0.50	No
Dominik Zumbuhl (Harvard)	0.50	No
Christian Barthel (Harvard)	0.50	No
Ian Chan (Harvard)	0.50	No
Andrew Vidan (Harvard)	0.50	No
Parisa Fallali (Harvard)	0.50	No
Muhammed Yildirim (Harvard)	0.50	No
Yishifumi Nishi (Tokyo)	1.00	No
Shinichi Amaha(Tokyo)	1.00	No
Tetsuo Kodera (Tokyo)	1.00	No
Yuichi Igarashi (Tokyo)	1.00	No
Kenichi Hitachi (Tokyo)	1.00	No
Akihiko Takahashi (Tokyo)	1.00	No
Jun Sugawa (Tokyo)	1.00	No
Yosuke Kitamura (Tokyo)	1.00	No
Akihiro Soma (Tokyo)	1.00	No
Testuya Asayama (Tokyo)	1.00	No
Aihiko Numata (Tokyo)	1.00	No
Yoshifumi SHimizu (Tokyo)	1.00	No
Yasuaki Yokoyama (Tokyo)	1.00	No
Shinpei Yamaguchi (Tokyo)	1.00	No
Jihan Kim (UIUC)	0.25	No
FTE Equivalent:	**24.75**	
Total Number:	**32**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED	
P. Matagne (UIUC)	1.00	No
D. Melnikov (UIUC)	1.00	No
G. Yu (NRC)	1.00	No
L.M.K. Vandersypen (Delft)	1.00	No
C. Mayer (Delft)	1.00	No
W.G. van der Wiel (Delft-Tokyo)	1.00	No
P. Jarillo-Herrero (Delft)	1.00	No
S. Erlingsson (Basel)	1.00	No
J. Lehmann (Basel)	1.00	No
C. Egues (Basel)	1.00	No
H.-A Engel (Basel)	1.00	No
F. Meier (Basel)	1.00	No
Jason Petta (Harvard)	1.00	No
Michel Piodo Ladriere (Tokyo)	1.00	No
Tsuyoshi Hatano (Tokyo)	1.00	No
Alessandro Pioda (Tokyo)	1.00	No
Toshiaki Obata (Tokyo)	1.00	No
Yun Sok Shin (Tokyo)	1.00	No
Takeshi Ota (Tokyo)	1.00	No
Mike Stopa (Tokyo)	1.00	No
Toshiaki Kubo (Tokyo)	1.00	No
Takeshi Inoshita (Tokyo)	1.00	No
Wataru Izumida (Tokyo)	1.00	No
FTE Equivalent:	**23.00**	
Total Number:	**23**	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
J.P. Leburton (UIUC)	1.00	No
B. Altshuler (Columbia)	1.00	No
D.G. Austing (NRC)	0.00	No
L. Kouwenhoven (Delft)	0.00	No
D. Loss (Basel)	0.00	No
C.M. Marcus (Harvard)	1.00	No
S. Tarucha (Tokyo)	0.00	No
R.M. Westvelt (Harvard)	1.00	No
K. Ono (Tokyo)	0.00	No
M. Yamamoto (Tokyo)	0.00	No
FTE Equivalent:	**4.00**	
Total Number:	**10**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	
Sapan Agarwal (UIUC)	0.00	No
Nathaniel Craig (Harvard)	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Personnel receiving masters degrees

NAME	
Jihan Kim (UIUC)	No
Lingxiao Zhang (UIUC)	No
Yishifumi Nishi (Tokyo)	No
Jihan Kim (UIUC)	No
Lingxiao Zhang (UIUC)	No
Yishifumi Nishi (Tokyo)	No
Testuya Asayama (Tokyo)	No
Aihiko Numata (Tokyo)	No
Akihiko Takahashi (Tokyo)	No
Jun Sugawa (Tokyo)	No
Shinichi Amaha(Tokyo)	No
Akihiro Soma (Tokyo)	No
Yasuaki Yokoyama (Tokyo)	No
Kenichi Hitachi (Tokyo)	No
Tetsuo Kodera (Tokyo)	No
Yuichi Igarashi (Tokyo)	No
Shinpei Yamaguchi (Tokyo)	No
Shinichi Amaha (Tokyo)	No
Yosuke Kitamura (Tokyo)	No
Total Number:	**19**

Names of personnel receiving PHDs

NAME	
R. Hanson (Delft)	No
L.H. Willem van Beveren (Delft)	No
B. Coish (Basel)	No
H.A. Engel (Basel)	No
A. Johnson (Harvard)	No
R. Potok (Harvard)	No
J. Folk (Harvard)	No
A. Vidan (Harvard)	No
J. Taylor (Harvard)	No
D. Zumbuhl (Harvard)	No
I. Chan (Harvard)	No
P. Fallahi (Harvard)	No
Shinichi Amaha (Tokyo)	No
Yishifumi Nishi (Tokyo)	No
Michihisa Yamamoto (Tokyo)	No
Tetsuo Kodera (Tokyo)	No
Total Number:	**16**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Summary of Accomplishments

Task 1) : Theory of spin relaxation and decoherence in quantum dots. (D. Loss)

Loss has theoretically investigated a variety of problems related to spin qubits in quantum dots, with primary focus on decoherence issues, the most important scalability issue in quantum computing. He has shown that the most important source of spin relaxation in quantum dots is dominated by spin phonon interaction induced by spin orbit coupling. He made various predictions of the relaxation time in quantum dots as function of dot size, geometry and magnetic field dependence, which is very specific for GaAs. All these predictions have been verified experimentally, mostly by groups in this consortium (Delft, Harvard, and Tokyo), but also by other groups (in particular, Kastner's group at MIT).In contrast to this, the spin decoherence times turn out to be dominated by hyperfine interaction of the electron spin with thenuclear spins of the lattice. He spent considerable effort to understand this type of decoherence in single and double quantum dots (the latter being motivated by ongoing experiments in the consortium). He found many new and interesting results, showing that decoherence due to many other spins is non-Markovian and characterized by power laws. Some of our predictions in double dots such as power laws, and most recently also universal phase shifts have been experimentally confirmed (Harvard and Delft). This is agreement between theory and experiment is very reassuring and demonstrates that we have understood the essential mechanisms for decoherence, and this gives strong support and credibility to our further predictions that the nuclear spin problem can be controlled in GaAs quantum dots. In this context this overall effort has been very successful and has achieved essentially all milestones such as single spin read out (Delft), sqrt-of-swap (Harvard) and single spin Rabi oscillations. At the end of this program and based on our theoretical progress in understanding the sources of decoherence one can now say with great confidence that spin qubits in solid state systems are one of the most promising candidates for a scalable quantum computer.

Task 2): Fabrication and characterization of coupled quantum dots (R.M Westervelt)

Westervelt studied the behavior of few-electron double and triple quantum dots. He started with 1-electron tunnel-coupled double dots, and then developed few-electron triple dots arranged in a ring. These devices were formed by gates in a GaAs/AlGaAs heterostructure. A charging rectifier that operated as a quantum ratchet was demonstrated by a triple-dot device. The Kondo effect in 1- and 2-electron quantum dots was observed in a triple dot device, including nonequilibrium structure. Electrons inside a 1-electron GaAs dot were imaged using a cooled scanning probe microscope (SPM) tip as a movable gate. An SPM image of the dot shows rings of high conductance, corresponding to Coulomb blockade peaks as electrons are added to the dot. The image determines the energy shift of electrons inside the dot as the SPM tip is scanned above. This technique was used to measure the diamagnetic shift of the electron ground state inside a 1-electron GaAs dot. Westervelt also proposed a way to map the wavefunction for an electron state in the dot using an image of the energy shift, this technique is promising for the future. For coupled quantum dots, the SPM tip can add or subtract an electron from a given dot, providing a way to manipulate electrons inside multiple dot circuits. Westervelt contributed to theory from Loss's group on the entanglement of spins in an open system through collisions, and to the predicted occurence of Zitterbewegung oscillations of spin direction in narrow channels, caused by the spin-orbit interaction.

Task 3: Fabrication and characterization of laterally coupled vertical quantum dots (S. Tarucha and D.G Austing).

Tarucha's group has been successful in the fabrication of few electron laterally coupled vertical quantum dots. He developed various kinds of technologies for controlling (1) spin effects in quantum dots using Pauli spin blockade, and spin filtering effect, (2) charge and spin states in double quantum dots as a function of gate voltage and magnetic field, (3) exchange coupling in double quantum dots as a function of gate voltage and magnetic field, (4) coupling between electron spin and nuclear spin with exchange energy as a parameter, and (5) coherent operation of nuclear spin ensembles. He also proposed a new scheme of electron spin qubits using slanting Zeeman field. This scheme is much more relevant for scalability than those proposed to date.

Work on the development of three or more laterally coupled vertical dots for potential qubit circuits was initiated. Initial devices were designed and fabricated but it remains a challenge to reliably make such structures where all gates work and the inter-dot couplings are comparable and controllable. Simulations by Leburton proved insightful but also illustrate the extreme sensitivity of the inter-dot coupling to small variations in the structural parameters. An alternative strategy of coupling three or more vertical dots vertically was envisaged and will be pursued by Austing and Leburton. Experiments on weakly coupled vertical double dot structures with a single gate were successful. There were three areas of focus: i. Single particle states of one quantum dot were probed up to high energy with the 1s-like state of the other quantum dot. In a magnetic field, Fock-Darwin like spectra were measured and this is a way to assess in detail the symmetry of the underlying dot potential. This is useful for realistic device simulation. Furthermore, 2-, 3-, and 4- quantum level crossings were observed which will be investigated further for novel mixing effects; ii. Current resonances, current hysteresis, and slow quasi-periodic current oscillations (~10's second) at high bias, well outside the N=2 spin blockade regime, were observed. Measurements are being performed to see if this is related to electron spin- nuclear spin (hyperfine) coupling. If this is the case, then the influence of nuclear spin is more widespread than currently understood; iii. High bias I-V characteristics were measured, and modeling attempted. This is to test how well resonant tunneling barrier structures are understood in the context of resonant versus sequential tunneling, and scattering (including phonons).

Task 4): Read-out and spin detection in quantum dots

Kouwenhoven's group has been successful in developing a method for reading out the spin state of electrons in a quantum dot that is robust against charge noise and can be used even when the electron temperature exceeds the energy splitting between the states. The spin states are first correlated to different charge states using a spin dependence of the tunnel rates. A subsequent fast measurement of the charge on the dot then reveals the original spin state. He experimentally demonstrated the method by performing readout of the two-electron spin states, achieving a single-shot visibility of more than 80%. Kouwenhoven found very long triplet-to-singlet relaxation times (up to several milliseconds), with a strong dependence on the in-plane magnetic field.

Task 5): Measurement of decoherence and exchange modulation in coupled quantum dots (C.M. Marcus)

Marcus's group developed and measured singlet-triplet spin qubit, measured spin T2 using spin echo in a two-electron quantum dot, measured effect of finite exchange in preserving spin coherence in double quantum dot, realized two electron square-root-of-swap operation in a time <~ 1 ns. We also demonstrated electron mediated exchange between separated quantum dots (RKKY interaction).

Task 6): Quantum modeling of exchange coupling in realistic quantum dots (J.P. Leburton)

Leburton's group has developed comprehensive 3D self-consistent modeling tools to simulate exchange interaction between two electron spins, which is controlled by electric gate in experimental quantum dots in the presence of magnetic fields. Variations of the exchange interaction with magnetic fields reproduce the experimental values (Marcus, Tarucha), and in the triplet state can at best reach a few tenths of μeVs. In this process it was found that the exchange modulation by the gate field was caused by the coulomb repulsion between the electrons than by the modulation of the coupling barrier. In this respect, vertical quantum dots have a slight advantage in achieving higher exchange values than in planar dots because of the harder confinement offered by the mesa structure. Overall considerable insight into the influence of device design over the physics of exchange has been obtained by the new modeling tools.